E/CONF.39/A/41
29 Sept. 1962
ORIGINAL : ENGLISH

UNITED NATIONS CONFERENCE
ON THE APPLICATION OF SCIENCE AND TECHNOLOGY
FOR THE BENEFIT OF THE LESS DEVELOPED AREAS

Agenda Item : A. 3. 2

Canada

THE ROLE OF METEOROLOGY IN WATER RESOURCES DEVELOPMENT

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THE ROLE OF METEOROLOGY IN WATER RESOURCES DEVELOPMENT

J.P. Bruce

1. INTRODUCTION

1(a) An understanding of the hydrologic cycle is essential to the intelligent management of water resources for man's benefit. Meteorology is directly concerned with many aspects of the hydrologic cycle, particularly the circulation of water vapour in the atmosphere, precipitation and evaporation, and so should be able to contribute substantially to an understanding of the more hydrologic aspect of the cycle, the disposition in time and space of precipitated water. However, it may not be too clear just what the specific contributions may be made, and in what way meteorology may assist in solving water resources and flood control problems. This paper outlines some of these contributions. An approach to water problems through weather information and knowledge is often called hydrometeorology or in the terminology of the World Meteorological Organization "hydrological meteorology".

1(b) It will be seen from the examples in this paper that there are three main stages of water control projects in which hydrometeorological analyses are of value: (i) assessment of economic costs and benefits of a project, relative to alternative projects, (ii) design of control works and (iii) operation of the completed works. In addition, where control structures are uneconomical, river forecasting systems are of great value in minimizing damage and loss of life, and taking greatest advantage of the natural flow of rivers, and here hydrometeorology is of primary importance.

2. FLOOD AND DROUGHT FREQUENCY ANALYSES

2(a) Synthesizing Flood Records from Meteorological Data

2(a)(i) The economic value of a water conservation and flood control project depends on the frequency with which it is needed to overcome the variations of natural water supplies. In addition, in the design of a reservoir, a decision on the size of storage volume required must be based on statistical estimates of likely future high and low water events on the river or lake in question. In countries and regions fortunate enough to have 50 to 100 years or more of river flow and lake level data, such frequency analyses should be

based primarily on river flow data. However, many countries have a great deal more precipitation data accumulated than streamflow data and in such cases methods of estimating flood records from precipitation records are of great value.

2(a) (ii) For watersheds in the range 25 to 5000 sq. mi, storm rainfall-runoff correlations and unit hydrographs can be developed for any period of joint precipitation-streamflow record and these may be used along with the longer records of precipitation in re-constructing previous flood events and thus effectively extending the length of river flow records. Such correlations are also used in river forecasting and usually involve 4 or 5 variables: storm rainfall volume, runoff volume, an antecedent precipitation index or a soil moisture index, a seasonal factor (often the week number of the year), and sometimes a storm duration factor. These correlations can be derived graphically or analytically from recorded events on the river. This approach has been taken to its logical extreme by Paulhus and Miller (1957) who showed that a whole annual maximum flood series for a river could be successfully estimated from regional rainfall data using rainfall-runoff correlations developed for that region, in the absence of any streamflow data for the particular basin in question. Once the annual maximum flood peak series has been synthesized or extended by means of precipitation data, an extreme value frequency analysis by the method of Gumbel (1954) say, will yield the magnitude of the peak flows for various return periods or inversely, various probabilities of occurrence.

2(b) Rainfall Intensities for Drainage Design

2(b) (i) Hydrologic design problems on very small watersheds (5 sq. mi.) include decisions on culvert sizes, design of storm sewer systems for cities, spillways for farm pond dams, and even drainage facilities for roofs. Streamflow data are rarely available for such small watersheds and these watersheds are small enough that their rainfall intensity regimes can be represented by data from one rain gauge. In such cases various formulae such as the "rational method" involving rainfall intensity are used in estimating peak discharges. The rainfall intensity selected for use in the formulae is for a specific frequency or return period. The return period used is dependent on the economics of the situation. Given an estimate of the damage that would be done should the structure's capacity be exceeded by various amounts, and the frequency with which such flows are likely to occur, the most economical design can be achieved. Most storm sewers are designed for 5 to 10 year return period amounts.

2(b) (ii) In many countries not enough observed rainfall intensity data are available to perform frequency analyses for drainage design. In such cases, empirical methods developed by Hershfield and Wilson (1957) may be used. These permit computation of short duration rainfall intensities of various frequencies from one-day rainfall data, and numbers of thunderstorm days. Where limited amounts of rainfall intensity data are available, generalized maps can be drawn after obtaining relationships between the short duration data available and longer duration, 6, 12 or 24 hour data, more generally available. (Bruce 1959). It might also be noted that relatively simple methods for undertaking the Gumbel extreme value frequency analyses, have recently been summarized by Kendall (1959). These methods can be used

for either rainfall intensity or streamflow data. They involve computing the mean and standard deviation of the series of annual maximum values and applying a simple table or graph for computation of amounts for various return periods or probabilities.

2(c) Drought Frequencies

2(c) (i) In connection with provision of storage reservoirs and farm ponds for tobacco irrigation in Southwestern Ontario, an assessment was needed of the frequency with which various volumes of irrigation water would be required, during the critical growth period June 1 to August 15. It was found that the mean storage capacity of the porous sandy soil was about 1 inch. It was assumed that the plants would draw water from the soil at the potential evapotranspiration rate until the soil water storage was completely withdrawn. Day by day soil moisture budget calculations were undertaken for 20 years of record. In these calculations it was assumed that the soil was saturated on June 1, that this water was gradually depleted between rains at the rate of potential evapotranspiration calculated by the Thornthwaite method and that rain added to the storage water up to a maximum of one inch. The sums of potential evapotranspiration amounts after soil moisture had been depleted to zero were assumed to be measures of the amounts of irrigation water that should be applied to the crop. Fortunately, measurements of irrigation volumes actually applied by farmers in the area were available for a few years, and corresponded quite closely to the computed amounts. Then as the 20 years of water deficiencies, so calculated, appeared to be normally distributed about a mean value, normal probability tables were used to predict how frequently various volumes of irrigation water would be required. The economics of providing storage facilities for the 5, 10 or 15 year return period "drought" could proceed from there. More complicated soil moisture budgeting procedures using meteorological factors have been developed by Holmes and Robertson (1959) and other workers, primarily for use in operationally scheduling application of irrigation water.

3. MAXIMUM PRECIPITATION AND FLOODS

3(a) Requirement for Physical Analysis

3(a) (i) Large dams, particularly those constructed upstream from urban centres, must be designed to very stringent safety criteria. In some cases the spillways of such dams are designed to accommodate an estimate of the physical upper limit to flow in the river, or at least are designed in the light of such an estimate. Physical estimates of maximum flood flows are based on determinations of maximum storm rainfall, snow accumulation and snowmelt. An example will serve to illustrate why statistical techniques are not relied on entirely for estimating maximum floods. The Humber River near Toronto was gauged for 10 years prior to 1954, and the highest flood flow this 344 sq. mi. watershed produced was 10,000 cfs. A frequency analysis of the maximum flood flows would have assigned a very low probability indeed to a flow of 40,000 cfs. Yet on October 15, 1954, a 45,000 cfs. flood rolled down the river doing many millions of dollars in damage and drowning 80 people. The storm which produced the heavy rainfall was nearly identical, meteorologically, with a storm which occurred in September 1878, which also caused floods and

devastation in the Great Lakes region but mostly in the United States. In short, a statistical analysis of streamflow data even on a regional basis would not have suggested the need for designing for such an extreme event, but a study of historical storms in the region would have permitted a prediction of the possibility. Experiences such as this have occurred in many regions and have led to a physical approach to estimates of maximum floods in cases where the ultimate in safety is required.

3(b) Rainstorm Analysis Method

3(b) (i) The first step in assessment of the physical upper limit to storm rainfall is to perform depth-area-duration analyses of the rainfall production of major storms of record in the area in question, and in climatologically similar adjacent areas. Analysis procedures are described in a U S. Weather Bureau manual (1946). The table or graph resulting from such storm analyses gives precipitation depth vs. area for fixed durations, usually 6, 12, 18, 24 hrs. etc., during which the areal precipitation was greatest. That is, the data are maximum in a time sense, averaged areally outwards from the storm centre or centres. It is generally assumed that among the storms of record in a region at least one has functioned at near maximum mechanical efficiency in converting the water vapour in the atmosphere into rain. Thus if the rainfall of each severe storm of record is adjusted for maximum moisture content of rain-producing air masses in the region at that time of year, an estimate can be made of the maximum storm precipitation for various areas and durations. The moisture maximization factor can be estimated from dew point data in the absence of upper air observations of air mass water vapour content. (U.S. Weather Bureau 1947).

3(b) (ii) The method applies of course to regions in which travelling extra-tropical storms or hurricane-type storms produce heaviest rainfalls. For tropical regions, and where only a few years of data exist, special techniques have been successfully developed and applied. An example is the study of the Bocono River basin in Venezuela by Riehl and Byers. (1960).

3(c) Maximum Snow Accumulation

3(c) (i) Three methods are available for estimating the upper limits to seasonal snow accumulations, the "partial season" method, snowstorm maximization and the statistical approach. The first of these assumes that one can combine the greatest amounts observed in months, or fortnights, or shorter periods, regardless of the year of occurrence to give a "synthetic" year of very high snowfall. The second method involves applying moisture maximization factors to each snowstorm of several of the larger observed snowfall seasons. The maximized storm snowfalls when summed for the season yield maximum snow accumulation estimates based on the assumption that all the storms could have occurred at maximum water vapour content of the precipitation-producing air masses. A statistical study by a method of extreme values, of annual maximum observed snow depths on the ground, serves to verify results obtained by the other two approaches. In applying these methods to the region of Quebec along the north shore of the St. Lawrence River near Baie Comeau, the figures from the 3 methods tended to corroborate each other

and a value of 200% of greatest observed winter snowfall was determined as the upper limit to snowfall in this region (Bruce 1962).

3(d) Maximum Melting Rates of Snow

In years past the number of degree-days above 32°F (0°C) were frequently used to correlate with snowmelt rates and volumes. More recently a more thorough understanding of the physical factors affecting snowmelt rates has been obtained and basin melt equations derived involving insolation, snow surface albedo, air temperature, humidity, wind and rainfall. (U.S. Corps of Engineers 1956). Preliminary tests indicate the superiority of these basin equations in estimating maximum melting rates (Bruce 1962).

3(e) Maximum Flood Flows

In the ways outlined above the maximum water supply to a watershed from rain and melting snow can be estimated. It remains then, to convert this into a maximum flood hydrograph for design purposes. Rainfall-runoff correlations permit estimation of the proportion of the water supply that will appear in river channels during the peak flood period, and unit hydrograph techniques are applied to determine the distribution in time of this volume of runoff and the peak discharges that will result.

4. OTHER METEOROLOGICAL ASPECTS OF DAM AND RESERVOIR DESIGN

4(a) Evaporation Losses

4(a) (i) In many parts of the world evaporation losses from lakes and reservoirs may be large in proportion to the volume of water stored and must be accurately estimated, preferably prior to the construction of the storage facility, so that suitable allowances may be made for this loss. In Weyburn Reservoir, Saskatchewan, for example, the evaporative loss is approximately equal to the annual consumption of water by the town. The Lake Hefner and Mead experiments (U.S. Dept. of Interior 1954, 1958) in western United States have critically reviewed the various formulae and instruments for estimation of lake and reservoir evaporation. Among the findings were that relatively simple mass transfer types of equations of the "Dalton" form are as suitable as any for estimating lake and reservoir evaporation, in the climatic zone of the experiments. However two main problems remain. How can the surface water temperature of a yet-to-be-formed reservoir be accurately estimated and how well do the Lake Hefner and Mead findings apply in different climatic regions? Energy balance techniques along with limnological knowledge of temperature regimes of small lakes have been successfully used in solving the first of these problems. The second requires research in many parts of the world.

4(a) (ii) One other important development in recent years has been the derivation by Kohler, Nordenson and Fox (1955) of corrections to U.S. Weather Bureau Class "A" evaporation pan data for net heat transfer through the pan walls, to permit estimation of lake evaporation for water bodies of negligible heat storage.

4(b) Wind Set-up and Waves

4(b) (i) Lakes and reservoirs, particularly if shallow and oriented with their long axis in the direction of strong winds are subject to set-up and seiche effects due to winds. There must be enough free-board allowed on earth-fill dams so that water does not spill over the structure under critical wind conditions. Although the state of theoretical knowledge of the wind stress on water surfaces is not entirely satisfactory, enough is known to make reasonable estimates of maximum set-up and wave heights from data on maximum wind speeds in the critical direction. On shallow lakes with long axes parallel to favoured directions of strong winds the water level at one end of the lake may be raised or lowered by as much as 4 or 5 feet by wind set-up. Wave heights on top of this of 3 or 4 feet are not uncommon. The cost of raising a dam 7 or 8 feet for protection against such events is likely to be great. Thus accurate estimates of the maximum magnitude of this effect and the meteorological likelihood of winds required to produce maximum set-up and waves, following meteorological events which would lead to a full reservoir, are essential to economical and safe design.

5. HYDROLOGICAL FORECASTING

5(a) River Forecast Requirements

The day-to-day or month-to-month prediction of instantaneous flows or volume flows of a river may be extremely valuable in many ways. On watersheds where flow is uncontrolled by dams, such forecasts permit issuance of flood warnings as needed, may permit more efficient navigation, log-driving, and regulation of diversions of water for irrigation and other purposes. For controlled or partially controlled rivers, reliable forecasts of river flow permit more efficient use of dams for controlling floods, water supply, power production, maintenance of downstream flow volume and other purposes. This is especially so where reservoirs are of the multi-purpose type. It can be seen that if a dam is to be used for flood control only, all that is required is that the reservoir be left empty at all times to accommodate any flood that may occur. However, if it is to be used for water conservation as well, then a high reservoir level must be maintained to meet the needs of the water users. It thus becomes necessary to know by how much the reservoir level should be lowered, and by what time, in order to accommodate a flood. If drawn too low, the conservation lake level is not restored when the flood is over; if not drawn down enough, the dam's capacity is overtaxed and unnecessary downstream flood damage occurs. The value of accurate forecasts increases with the number of purposes to which the dam is put, and the problem becomes more complex and important if more than one dam per river must be regulated.

5(b) Methods of River Forecasting

The smaller the watershed the greater is the need for a meteorological approach to river forecasting. On small watersheds, of the order of a few thousand square miles or less, the response of the river to a rainstorm or to snowmelt is so rapid that only forecasts based on weather observations or weather forecasts can be issued far enough in advance to be of value to users. On large

rivers, it is possible in some cases to forecast the flow on the main stream by routing procedures applied to river flow observations on the tributaries and in headwaters regions. However even here, if reliable forecasts, from meteorological data, of tributary flows are available, a much greater time advantage can be gained in issuance of main stream forecasts. Headwaters or small watershed forecasts are usually based on storm rainfall-runoff correlations as described in section 2(a) (ii). Runoff volumes for individual storms are forecast by these correlation equations or graphs and converted into river flow and stage estimates by unit hydrograph techniques, which also permit prediction of the magnitude/time of peak flow. Storm rainfall volumes are usually based on observed rainfall amounts. Quantitative rainfall forecasting has not yet developed to a stage where it can be relied upon for river forecasts. However rainfall predictions often do serve to alert rainfall network observers to the need for forwarding information to a river forecast centre. Techniques most frequently used in North America involve the antecedent precipitation index as a measure of the wetness of the basin prior to the onset of a storm. However Kohler (1957) has tested a method for using evaporation data along with antecedent precipitation data to more accurately assess this factor. During non-storm periods as well, evaporation data can assist in forecasting the gradual recession of streams, although this is usually done by means of typical recession curves developed from past flow records at the point in question.

5(c) Special Hydrologic Forecasts

The flow of many rivers is controlled by the level of an upstream lake, and in some cases fluctuations of lake level due to wind set-up and seiches can effect marked changes in river flow. For example on the Niagara River, variations of flow within a few hours from 180,000 cfs. to 320,000 cfs. have been observed as a result of wind-induced fluctuations of the water level in eastern Lake Erie. The Ontario Hydro-Electric Power Commission employs a meteorologist, one of whose duties is to predict the winds on Lake Erie, the set-up and seiches these will induce and the effect on the flow of the Niagara. This in turn affects the amounts of power that can be produced at the Niagara Falls generating stations, and the need for providing power from alternative sources.

6. CONCLUSIONS

This paper discusses briefly only a few examples of the ways in which meteorological theory and data can assist in making efficient use of water resources and in controlling floods or minimizing their harmful effects. It has not been possible to discuss the role of meteorology in surveying surface water resources, weather modification by cloud seeding, seasonal runoff forecasting, reduction of evaporation by mono-molecular films of hexadecanol and shelterbelts, the value of precipitation forecasts in irrigation scheduling, or the role of meteorology in assessing the natural water balance of regions and the modifications to microclimate and the water balance that can be effected by manipulation of vegetation. However, I think it is clear from the limited number of examples discussed that a much greater effort in the field of hydrometeorology is warranted in many countries, and in particular the developing countries of the world. Only with such an effort will we manage the world's vital fresh water resources intelligently and well.

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